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(54) Title: TRAVELLING WAVE PARTICLE SEPARATION APPARATUS

(57) Abstract

Travelling wave particle separation apparatus is provided having a flat spiral of electrodes (1, 2, 3, 4) or a helix of similar electrodes on a cylindrical former. Only four electrical connections need to be made.

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Travelling Wave Particle Separation Apparatus

The present invention relates to travelling wave particle separation apparatus, which may be travelling wave field migration (also known as travelling wave electrophoresis) apparatus, having an improved electrode configuration.

As described in WO94/16821, particles can be manipulated by subjecting them to travelling electric fields. Such travelling fields are produced by applying appropriate voltages to microelectrode arrays of suitable design. The microelectrodes have the geometrical form of parallel bars, which may be interrupted by spaces to form channels, as shown in figure 1 and may be fabricated using standard metal sputtering and photolithographic techniques as described by Price, Burt and Pethig, *Biochemica et Biophysica*, Vol.964, pp.221-230. Travelling electric fields are generated by applying voltages of suitable frequency and phases to the electrodes as described in a paper, title "Separation of small particles suspended in liquid by nonuniform travelling field", by Masuda, Washizu and Iwadare, *IEEE Transactions on Industry Applications*, Vol.IA-23, pp.474-480. Masuda and his coworkers describe how a series of parallel electrodes (with no channels) supporting a travelling electric field can, in principle, be used to separate particles according to their electrical charge and size (weight). Masuda et al have not however described a practical demonstration of such a particle separation method.

In a paper entitled "Travelling-wave dielectrophoresis of microparticles" by Hagedorn, Fuhr, Müller and Gimsa (*Electrophoresis*, Vol.13, pp.49-54) a method is shown for moving dielectric particles, like living cells and artificial objects of microscopic dimensions, over

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microelectrode structures and in channels bounded by the electrodes. The travelling field was generated by applying voltages of the same frequency to each electrode, with a 90° phase shift between neighbouring electrodes.

5

In "Electrokinetic behaviour of colloidal particles in travelling electric fields: Studies using Yeast cells" by Y Huang, X-B Wang and R Pethig J. Phys. D. Appl. Phys. 26 1993 1528-1535, an analysis supported by experiment is made of the "travelling-wave dielectrophoresis" (TWD) effect described by Hagedorn et al (paper cited above). The phenomenological equation

$$\mu = - \frac{2\pi \epsilon_m r^2}{3\lambda\eta} A^2(0) \text{Im} [f(\epsilon_p^*, \epsilon_m^*)]$$

15

is developed by Huang et al, to show that the TWD velocity is a function of the square of the particle radius (r), the square of the electric field strength ($A(0)$), the periodic length of the travelling field (λ), medium viscosity (η) and the imaginary part of the Clausius-Mossotti factor $f(\epsilon_p^*, \epsilon_m^*)$ defining the dielectric properties of the particle and the suspending medium in terms of their respective complex permittivities ϵ_p^* and ϵ_m^* . This equation provides, for the first time, a practical guide for the design of travelling wave electrode systems for the manipulation and separation of particles.

Although the phenomenon in question is usually termed "travelling wave dielectrophoresis", this is something of a misnomer as the force which acts on the particles to produce translational movement is not the dielectrophoresis force but rather that which acts in electrorotation. This force is related to the imaginary component of the polarisability of the particle within its surrounding

medium. However, as is discussed in more detail below, particle migration only occurs for travelling wave frequencies which produce negative dielectrophoretic forces on the particle. (Dielectrophoretic forces are related to the real component of the polarisability of the particle within its surrounding medium.) These forces are responsible for lifting the particle away from the electrodes and the channel between the electrodes. We accordingly prefer to refer to the phenomenon called previously "travelling wave dielectrophoresis" by the name "travelling wave field migration" (TWFM). To obtain TWFM, two separate criteria have to be met. First, a frequency must be selected at which the dielectrophoresis force acting on the particles is negative, ie such as to repel the particles from the electrodes. This, we have found requires the real component of the dipole moment induced in the particles to be negative.

Second, the frequency selected has to be such that the imaginary component of the dipole moment induced in the particles is non-zero (whether positive or negative) to produce a force displacing the particles along the array of electrodes.

The field conditions may also be chosen such that some particles are held by the electrodes and do not migrate or follow any bulk flow of the liquid in which they are contained whilst other particles are not held by the electrodes and are either essentially unaffected or migrate in one or other direction with respect to the field.

In travelling wave particle separation apparatus, an array of electrodes is provided forming a "ladder" along which particles may be caused to migrate under suitable field conditions or on which particles may be held. The electrodes may form a linear ladder or may be arranged as

concentric circles. The phase of the voltage applied to successive electrodes will differ in a repeating pattern so that each n^{th} electrode will be at the same phase (where n is an integer). This presents a difficulty in physically 5 wiring the electrodes to a voltage source in that separate connections need to be provided to each electrode or to groups of electrodes in which groups each electrode is spaced from the next by $n-1$ electrodes belonging to other groups. If printed wiring connections are provided, there 10 will need to be insulated crossing points.

This difficulty is avoided according to the present invention, in which there is provided travelling wave particle separation apparatus having an electrode array 15 which comprises a plurality of continuous electrodes running side by side with one another in a path so shaped that a particle migrating transverse to the electrodes would cross each electrode repeatedly and such that the order in which the electrodes would be encountered by such 20 a particle migrating transverse to the electrodes at each crossing thereof would be the same.

Of course it will be appreciated that the particles are not necessarily actually caused to migrate over the 25 electrode array in the use of the apparatus.

Examples of electrode arrangements in accordance with the invention are a flat spiral, a helix of constant diameter, or a helix of decreasing diameter, i.e. a conical 30 spiral.

The nature of the particles which are separated may vary widely. The particle may be of a size to be visible using a light microscope (a microscopic particle) or may be 35 smaller (a sub-microscopic particle). The particle may be labelled to assist identifying or tracing it and may be

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detected using labels such as luminescent, fluorescent and electromagnetic radiation absorbent labels.

Examples of the former type of particle include
5 mammalian cells, plant cells, yeast cells, plastics micro-beads, chromosomes undergoing meiosis and mitosis and oocytes.

Examples of the second type would include bacterial
10 cells, viruses, DNA or RNA molecules, proteins, other bio-molecules, and chromosomes.

Optionally, one may treat particles to be separated to alter their field migration properties to assist separation
15 or so that the act of separation demonstrates that the expected alteration has occurred. Methods of altering field migration properties are described in detail in WO94/16821.

20 There are preferably from 2 to 10 electrodes, more preferably from 2 to 5 electrodes. As the electrodes are continuous, there is only a need to make one electrical connection per electrode for the whole apparatus and so the need for numerous or crossing connection paths is avoided.

25

The process of travelling wave particle separation may be carried out using an array of electrodes subjected to phased electric fields normally such that every nth (where 30 n is an integer) electrode is in phase. This periodicity defines the effective wave length of the travelling wave field produced. This wave length is optimally about ten times the average diameter of the particle to be moved under TWFM, eg from 5 to 20 times or more preferably 8 to 35 12 times said average diameter. For particles which are not roughly circular, it is the length in the direction

transverse to TWFM movement which is of significance.

The electrodes may be formed, depending on the dimensions required, using any of the standard techniques for patterning and manufacturing microscopic structures. For example the electrodes can be produced by:

screen printing;

deposition of electrode material (eg by electroplating or sputter deposition) followed by one of the following patterning techniques:

15 direct writing using an electron beam followed by etching (eg wet chemical etching, dry plasma etching or focused ion beam etching);

20 writing by exposure through a photolithographically generated mask followed by etching - the mask may be generated for example by visible, ultra violet, X-ray or electron beam lithography;

25 excimer laser ablation;

patterning followed by deposition of the electrode material (as in the X-ray LIGA process).

30 The invention will be further described and illustrated with reference to the accompanying drawings, in which:

35 Figure 1 shows a first arrangement of electrodes for use in the invention; and

Figure 2 shows a second arrangement of electrodes for use in the invention.

As shown in Figure 1, a first embodiment of the
5 invention has a flat spiral of electrodes printed on a substrate. There are four electrodes 1,2,3,4 to which are applied sinusoidal voltages of phases 90° apart, as shown. If the apparatus is run so as to cause migration of particles, the particles will migrate radially, crossing
10 the electrodes repeatedly, but always in the order 1,2,3 and 4.

In use a sample may be applied to the whole area of the electrode and the frequency of the field may be chosen
15 such that particles to be separated are attracted to the electrodes and are thus immobilised by the electrodes whilst other particles are repelled by the electrodes and so remain free. The free particles may be washed away. Alternatively, the field conditions may be selected such
20 that certain particles migrate toward the centre and others migrate toward the periphery, so that the particles are separated and may be collected. A benefit of the spiral configuration is that particles migrating to the centre will be concentrated.
25

In the arrangement shown in Figure 2, the electrodes are formed on the outer or more inner surface of a cylindrical former about which they follow a helical path. Once again, only four wiring connections are needed.
30

The apparatus may be used in a similar manner to the apparatus of Figure 1. If the field conditions are selected to immobilise certain particles only, a liquid may be flowed over the electrode array axially of the helix and
35 particles attracted to the electrodes may be harvested later by turning of the field and washing. Alternatively,

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the electrode array may be used as a field migration path for separating particles.

The sample volume will be limited essentially by the
5 area of the electrode array. As compared with the
electrode arrays described in WO 94/16821, the electrode
arrays shown here may be constructed to handle a much
larger volume. Thus whilst the earlier electrode arrays
were adapted to deal with a sample volume of about $10\mu\text{l}$,
10 the electrode arrays described above may be sized to accept
samples of greater than 5 ml, eg up to 50 ml or more.

Claims

1. Travelling wave particle separation apparatus having
5 an electrode array which comprises a plurality of continuous electrodes running side by side with one another in a path so shaped that a particle migrating transverse to the electrodes would cross each electrode repeatedly and such that the order in which the electrodes would be encountered by such a particle migrating transverse to the electrodes at each crossing thereof would be the same.
2. Apparatus as claimed in claim 1, wherein the electrode array comprises a substantially plane spiral of side by side electrodes.
15
3. Apparatus as claimed in claim 1, wherein the electrode array comprises a substantially constant diameter helix of side by side electrodes.
20
4. Apparatus as claimed in claim 1, wherein the electrode array comprises a helical spiral of side by side electrodes decreasing in diameter from one end of the helix to the other.
25
5. Apparatus as claimed in any preceding claim, wherein there are from 2 to 10 electrodes in said plurality.
30

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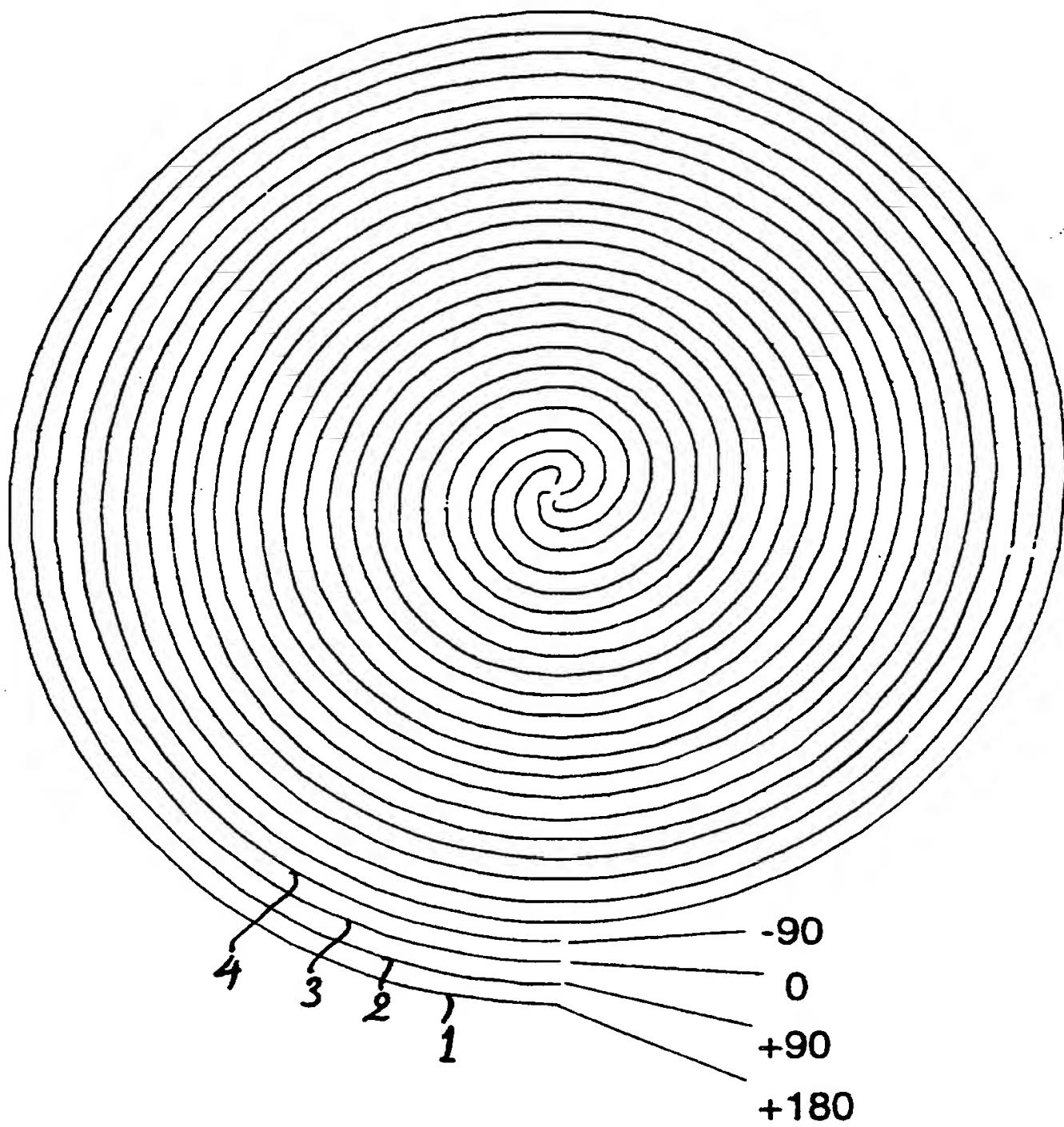


FIG. 1

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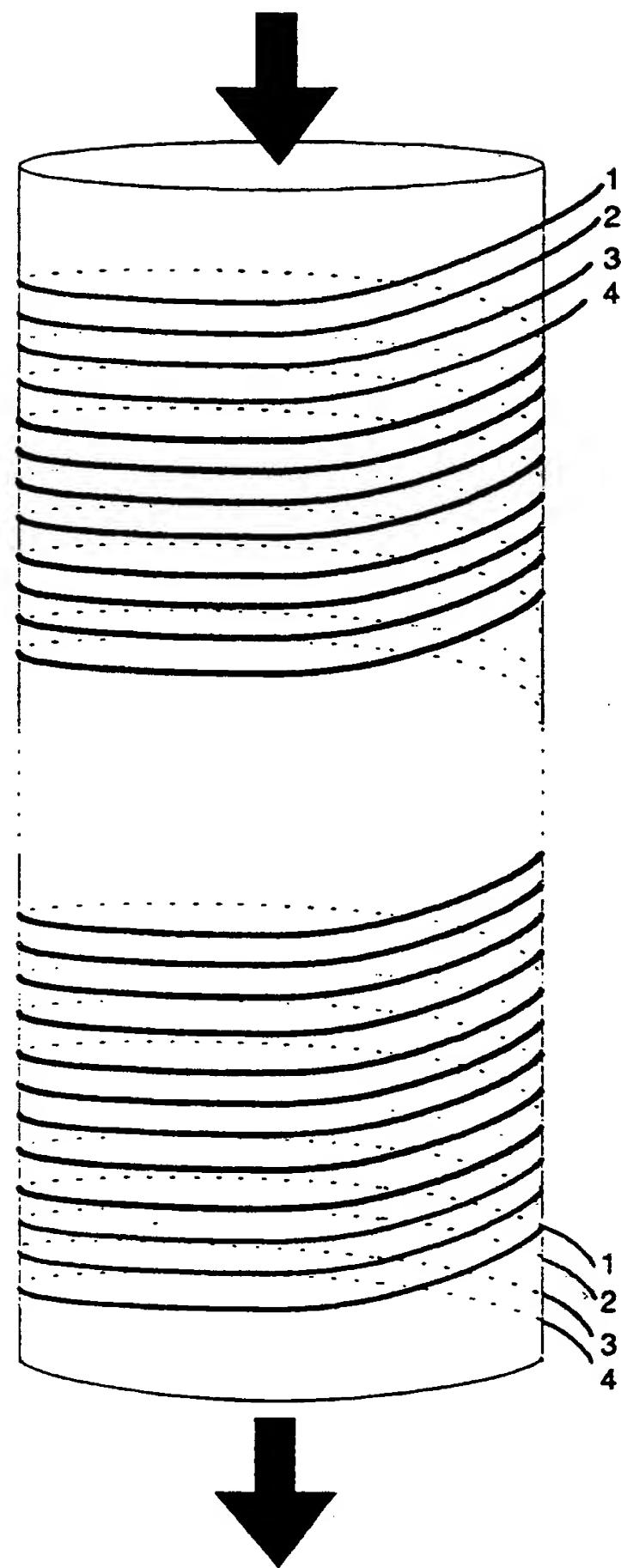


FIG. 2

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 96/00860

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 B03C5/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 B03C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	US,A,3 294 237 (D.WESTON) 27 December 1966 see column 4, line 24 - column 5, line 52; figure 1 --- X PATENT ABSTRACTS OF JAPAN vol. 001, no. 161 (M-053), 20 December 1977 & JP,A,52 105371 (INOUE JAPAX RES INC), 3 September 1977, see abstract --- X GB,A,423 523 (B.W.HOLMAN) 4 February 1935 see page 2, line 94 - page 3, line 2; claims 1,2,6,7; figure 8 ---	1,3,5 4 1,5 1,2 -/-



Further documents are listed in the continuation of box C.



Patent family members are listed in annex.

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Date of the actual completion of the international search

17 June 1996

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, vol. 1A, no. 3, May 1987, NEW YORK US, pages 474-480, XP002005853 S.MASUDA ET AL: "Separation of small particles suspended in liquid by nonuniform traveling field" cited in the application see page 474 see page 477, column 2, paragraph 2 - page 478, column 1, paragraph 1; figures 1,4 -----	1,5

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US-A-3294237	27-12-66	NONE	
GB-A-423523		NONE	